Pacific Science (1996), vol. 50, no. 2: 194–210

Water Quality in a Subtropical Embayment More Than a Decade after Diversion of Sewage Discharges[1]

EDWARD A. LAWS AND COLLEEN B. ALLEN[2]

ABSTRACT: Concentrations of chlorophyll *a* (chl *a*), particulate carbon and nitrogen (PC and PN, respectively), inorganic nutrients, and Secchi depths were measured from October 1989 to June 1992 in Kāne'ohe Bay, an embayment on the windward coast of O'ahu, Hawaiian Islands. Results were compared with values reported in 1978–1979, the year immediately following diversion of two sewer outfalls from the southeast sector of the bay. Nutrient enrichment experiments indicated that the bay is now distinctly nitrogen limited. In many respects the water column appears more oligotrophic now than in 1978–1979. Inorganic nitrogen and phosphate concentrations now border on the limit of detection by colorimetric methods. Chl *a* concentrations have declined by 35–40% (0.3–0.5 mg m^{-3}) and Secchi depths have increased by 15–35% (1.0–1.5 m) in the southeast sector of the bay since 1978–1979. This has happened despite a population increase of 7,762 persons in the watershed from 1980 to 1990. Characteristics of the water column are now remarkably similar in all sectors of the bay. About 40% of the phytoplankton chl *a* is accounted for by picoplankton. Pigment analyses indicate that diatoms and cyanobacteria make up ca. 45 and 25%, respectively, of the phytoplankton biomass. It is postulated that the drawdown of inorganic nutrient concentrations and increase in PN/chl *a* and PC/chl *a* ratios reflect a shift of the phytoplankton community toward smaller species characteristic of oligotrophic environments. An increase of PN in the central and northwest sectors of the bay is postulated to have been caused by an increase in nitrogen fixation and export from the barrier reef. There is no evidence that human population growth has altered nutrient loading from stream runoff.

KĀNE'OHE BAY IS A subtropical embayment on the northeastern side of the island of O'ahu in the Hawaiian Islands (Figure 1). Treated sewage was discharged directly into the bay for over 25 yr, first from the Kāne'ohe Marine Corps Air Station (1951) and later from the town of Kāne'ohe (1963). The deleterious effects of these discharges on the coral reef community in the bay became apparent by the early 1970s (e.g., Maragos 1972), and a few years later both outfalls were diverted to an ocean outfall off Mōkapu Point (Figure 1). The condition of the bay just before this diversion and the short-term response of the bay have been documented by Laws and Redalje (1979, 1982) and Smith et al. (1981). The condition of the bay's benthic community since that time has been documented to some extent in studies by Evans et al. (1986) and by Hunter and Evans (1995), but the water column community has received comparatively little attention.

Although the direct discharges of sewage to Kāne'ohe Bay were eliminated ca. 15 yr

[1] Research supported by a grant from the State of Hawai'i Department of Land and Natural Resources. School of Ocean and Earth Science and Technology contribution number 3944. Manuscript accepted 18 July 1995.

[2] University of Hawai'i at Mānoa, School of Ocean and Earth Science and Technology, Oceanography Department, 1000 Pope Road, Honolulu, Hawai'i 96822.

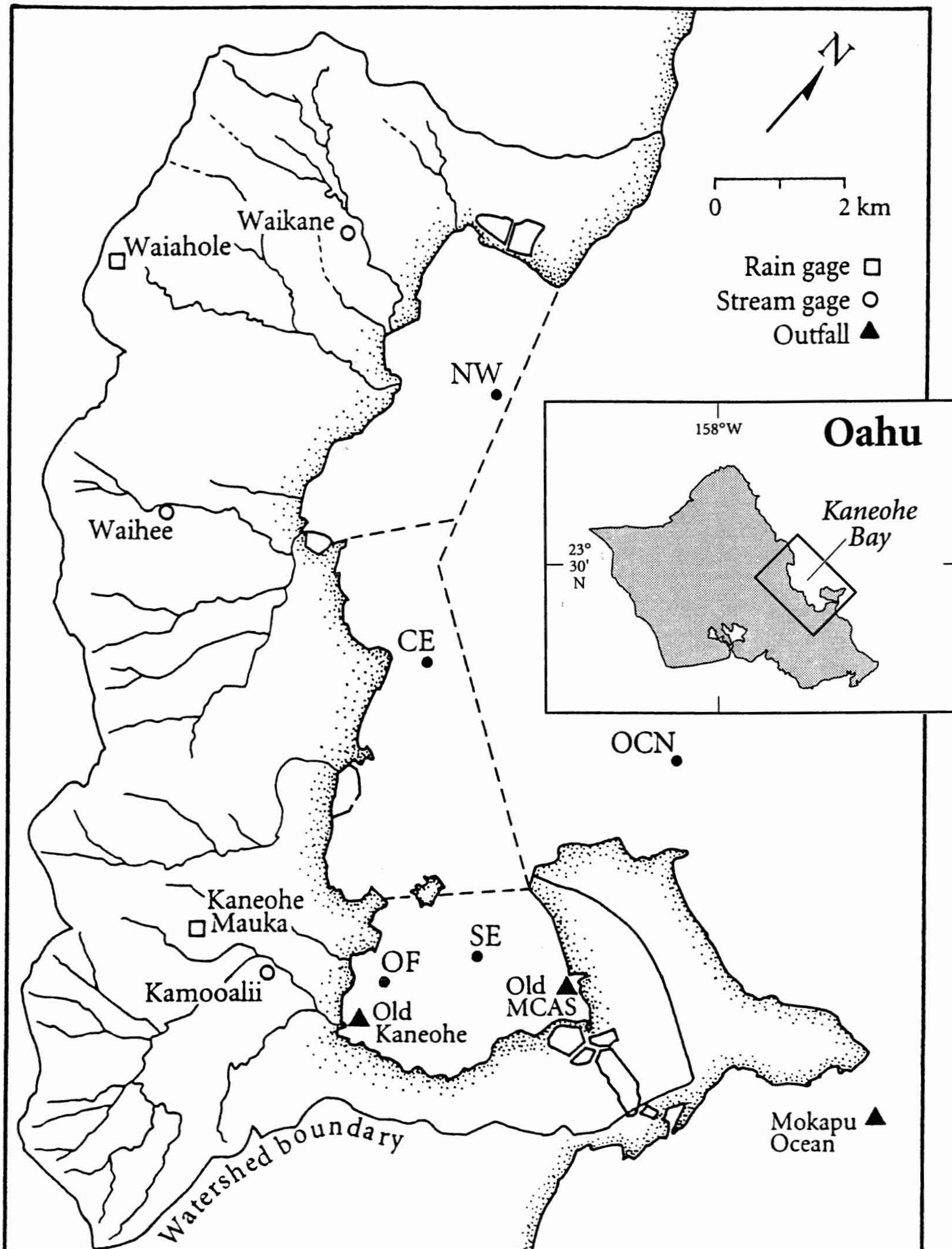

FIGURE 1. Kāne'ohe Bay and watershed showing locations of sampling stations, rain gauges, and stream discharge gauges.

ago, concern continues to grow over the impact of land runoff on water quality in the bay, particularly to the extent that such runoff may be affecting commercially and recreationally important fish stocks and the condition of the coral reef community. The human population of the watershed has been growing at ca. 1.8% per year since 1970 and by 1990 had reached 55,000 persons (DPEDT 1992). This population growth has been associated with land clearing and the creation of impervious surfaces, both of which have the potential to increase runoff and exacerbate eutrophication and sedimentation problems. For example, the runoff associated with a period of heavy rains during the winter of 1987–1988 delivered large quantities of sediment to the bay and stimulated a phytoplankton bloom that produced chlorophyll *a* (chl *a*) concentrations in excess of 40 mg m^{-3} in the southeast sector of the bay, almost four times the highest chl *a* concentration measured during the year immediately preceding the sewage diversions (Taguchi and Laws 1989). This incident dramatically illustrated the potential impact of land runoff on water quality in the bay and the sensitivity of the bay to land runoff as a result of the urbanization process.

Because of this realization, a study was undertaken to document conditions in the water column at four stations in the bay that had been studied during the 3.5-yr period from January 1976 to June 1979. That earlier work, funded by the Environmental Protection Agency (EPA), had documented conditions in the bay before and after diversion of the sewer outfalls from the southeast sector, which occurred in December 1977 and May 1978 (Smith et al. 1981). The results reported here summarize work carried out in the bay primarily from October 1989 to June 1992. The work was aimed at determining whether water quality and the condition of the phytoplankton cummunity had changed in the decade following the EPA study and, if so, whether the changes might have been caused by land runoff. A station immediately outside the bay was included in the 1989–1992 work to provide a comparison between conditions in the bay and nearshore ocean.

MATERIALS AND METHODS

Sampling was carried out at the five stations indicated in Figure 1. The bay is somewhat arbitrarily divided into a southeast, central, and northwest sector, indicated by the dashed lines in Figure 1. Stations SE, CE, and NW are located at the approximate centers of these three sectors. Station OF is located within ca. 100 m of the former outfall from the Kāne'ohe municipal sewage treatment plant. Station OCN is located at the approximate 30-m isobath directly off the mouth of a channel from the central sector of the bay. Water samples were collected using a Boston Whaler by immersing a 2-liter opaque plastic bottle to a depth of ca. 0.5 m. The top of the bottle was not opened until the bottle was submerged to avoid possible contamination from surface films. Bottles were immediately placed in an ice chest until they could be processed, usually within 1–2 hr of collection. Samples for chl *a*, particulate carbon (PC), and particulate nitrogen (PN) analysis were all filtered onto glass-fiber Whatman GF/F filters. The filtrates from these samples were retained for inorganic nutrient analyses.

Chl *a* samples were collected by filtering 400 ml of water. The filters were placed in plastic film cannisters in 100% acetone and allowed to extract in a freezer at $-20°$ C for at least 24 hr. The extracted pigments were separated from the filter and filter residue using the procedures outlined in Strickland and Parsons (1972). Chl *a* assays were made on a Turner fluorometer. Pheopigment corrections were made according to the procedures of Holm-Hansen and Riemann (1978).

Similar pigment analyses were also made to determine the size distribution of the chl *a*. For that purpose, 250 ml were filtered onto a 2.0-μm Nuclepore polycarbonate filter, and 100 ml of the filtrate was filtered onto a 0.2-μm Nuclepore filter. Picoplankton chl *a* was taken to be the chl *a* collected on the 0.2-μm filter. In calculating the contribution of the picoplankton to the total chl *a*, we assumed Whatman GF/F and 0.2-μm Nuclepore filters to retain all the chl *a* (Cuhel et al. 1983, Li et al. 1983, Chavez et al. 1995).

Nutrient enrichment experiments were carried out at stations OF and CE. Aliquots of 1000 ml were poured into duplicate polycarbonate bottles and incubated in front of a bank of daylight fluorescent lamps for a period of 2 weeks at a temperature of ca. 22° C. One set of duplicate bottles received no nutrient additions and served as the control. A second set received additions of trace metals, nitrate, phosphate, and vitamins in concentrations recommended for IMR medium (Eppley et al. 1967). The third and fourth sets received the same nutrient additions as the second set, except that phosphate and nitrate, respectively, were omitted. The chl *a* concentrations in each set of bottles were monitored over the 2-week incubation period, and the peak average chl *a* concentration for a duplicate set, measured fluorometrically on extracted samples (Strickland and Parsons 1972), was taken to be the yield for that treatment.

Samples for PC and PN analysis were first prescreened through a 183-μm mesh net to remove large zooplankton. Triplicate aliquots of 400–600 ml were then filtered onto precombusted (500° C) GF/F filters. The filters were frozen at −20° C before analysis. PC and PN assays were made on a Perkin-Elmer model 2400 elemental analyzer.

Analyses for nitrate plus nitrite, ammonium, phosphate, and silicate were made on a Varian model DMS spectrophotometer using the procedures in Strickland and Parsons (1972). Secchi depths were made using a 30-cm diameter white disk.

RESULTS

The results of our sampling are summarized in Table 1 and Figure 2. For comparative purposes, we have included in Table 2 results obtained at the four stations within the bay from June 1978 to June 1979, the year following the diversion of the sewer outfalls from the southeast sector of the bay. With the exception of silicate values, the comparisons in Table 2 are based on median values, which are much less influenced by errors and episodic events than mean values. Only mean silicate values are available from the 1978–1979 work, and the comparison of silicate concentrations is therefore based on means rather than medians. Judging from the similarity of the mean and median silicate concentrations in Table 1, there is little reason to prefer one measure over the other for purposes of comparing silicate values.

Perhaps the most striking feature of the results is the fact that phosphate, ammonium, and silicate concentrations were much lower in all parts of the bay during 1989–1992 than during 1978–1979. Nitrate concentrations were also much lower at the northwest sector sampling station during 1989–1992. Nitrate concentrations in the central and southeast sectors of the bay were 0.1 $\leq$ μM during both sampling periods.

In the nutrient enrichment experiments (Figure 2), there was a significant treatment effect on yields for both southeast and central sector water (Kruskal–Wallis test, $P <$ 0.001). Wilcoxon two-sample tests (Sokal and Rohlf 1969) revealed no difference between yields in the control bottles and the bottles lacking N ($P > 0.5$), but yields in the bottles lacking P were significantly different from and greater than yields in the bottles lacking N ($P < 0.01$). Yields in the bottles lacking P were significantly different for southeast and central sector water ($P < 0.005$), with the former being ca. seven times the latter. These results clearly implicate nitrogen as being the principal limiting nutrient for phytoplankton growth in the bay. The additional yield in the bottles lacking phosphate is a measure of the surplus phosphorus in the water. This surplus is evidently greater in the southeast sector of the bay than in the central sector of the bay.

Concentrations of PC and PN were higher during 1989–1992 than during 1978–1979 in the central and northwest sectors of the bay; the increases amounted to ca. 70%. In the southeast sector of the bay, however, PN and PC concentrations differed by no more than 10–20% between the two study periods. When concentrations of nitrate, ammonium, and PN were summed, there was a small decrease between 1978–1979 and 1989–1992 in the southeast sector of the bay, a 19% increase in the northwest sector of the bay, and

TABLE 1

KĀNE'OHE BAY WATER QUALITY SUMMARY, 4 OCTOBER 1989–10 JUNE 1992

		STATION				
COMPOUND	PARAMETERS	OF	SE	CE	NW	OCN
NO_3 (μM)	Median	0.08	0.08	0.07	0.17	0.06
	95% CI	0.07–0.11	0.06–0.10	0.06–0.09	0.12–0.21	0.025–0.075
	Mean	0.12	0.11	0.15	0.20	0.06
	Range	0–0.97	0–1.23	0–4.11	0–2.00	0–0.16
NH_4 (μM)	Median	0.02	0	0.03	0.05	0
	95% CI	0–0.05	0–0.04	0–0.04	0.01–0.08	0–0.05
	Mean	0.06	0.06	0.07	0.07	0.05
	Range	0–0.28	0–0.75	0–0.96	0–0.30	0–0.31
PO_4 (μM)	Median	0.03	0.05	0.03	0.03	0.06
	95% CI	0.02–0.05	0.04–0.05	0.02–0.04	0.02–0.04	0.05–0.06
	Mean	0.04	0.05	0.04	0.03	0.06
	Range	0–0.18	0–0.20	0–0.20	0–0.19	0–0.19
Si (μM)	Median	7.7	7.2	5.1	3.4	0.76
	95% CI	6.8–8.2	6.7–7.6	4.7–5.4	2.9–3.9	0.53–0.90
	Mean	7.9	7.1	5.4	3.9	0.85
	Range	3.3–25.8	1.8–13.9	1.6–20.8	1.3–13.1	0.17–2.00
Chl *a* (mg m^{-3})	Median	0.76	0.58	0.50	0.54	0.14
	95% CI	0.69–0.87	0.51–0.68	0.38–0.56	0.50–0.58	0.13–0.15
	Mean	0.99	0.65	0.51	0.55	0.16
	Range	0.20–4.84	0.15–1.58	0.13–1.55	0.12–1.22	0.06–0.82
Picoplankton chl *a* (mg m^{-3})	Median	0.30	0.23	0.19	0.22	0.09
	95% CI	0.25–0.35	0.21–0.25	0.17–0.21	0.21–0.24	0.08–0.10
	Mean	0.36	0.24	0.21	0.22	0.10
	Range	0.04–1.79	0.04–0.52	0.04–0.48	0.02–0.47	0.04–0.26
PN (mg m^{-3})	Median	44.5	42.5	33.8	36.4	9.3
	95% CI	40.5–47.2	35.6–48.4	31.1–38.3	30.2–40.6	8.3–10.8
	Mean	49.5	50.0	42.6	44.9	11.6
	Range	4.3–208	1.2–208	1.7–188	14.2–204	1.4–42.8
PC (mg m^{-3})	Median	229	224	180	206	47.2
	95% CI	215–245	199–244	167–205	182–224	44.9–50.0
	Mean	245	234	198	228	51.3
	Range	116–767	83.7–744	62.9–783	80.5–1,055	23.7–211
Secchi depth (m)	Median	6.0	7.0	7.0	7.0	23
	95% CI	6.0–6.5	6.0–7.0	7.0–8.0	6.0–7.0	21–24
	Mean	6.4	6.9	7.6	6.7	23.1
	Range	1.0–13.0	1.5–12.0	1.0–14.0	0.5–12.0	6.5–42

a relatively large increase of 45% in the central sector. Chl *a* concentrations were similar in the central and northwest sectors of the bay during the two study periods, but were ca. 35% lower in the southeast sector of the bay during 1989–1992. About 40% of the chl *a* in the bay was accounted for by picoplankton (Table 3). The corresponding figure for the offshore ocean was 64%. Secchi depths were closely correlated with chl *a* concentrations; the relationship between the two was similar during both study periods (Figure 3).

PC/PN ratios increased from the southeast sector to the northwest sector of the bay during both study periods, but were more uniform during 1989–1992. PN/chl *a* and PC/chl *a* ratios were higher during 1989–

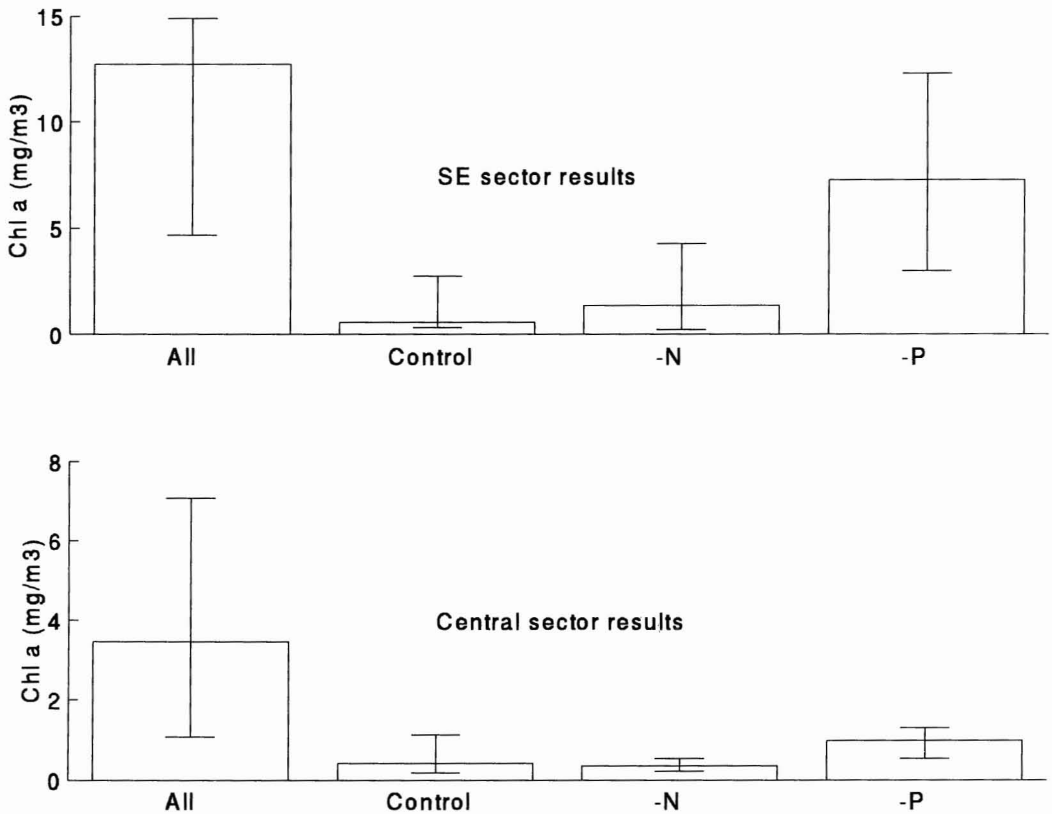

FIGURE 2. Results of nutrient enrichment experiments carried out during 1989–1992 in the southeast and central sectors of Kāne'ohe Bay. The ordinate is the median yield in flasks enriched with nitrogen, phosphorus, trace metals, and vitamins (All); no nutrients (Control); phosphorus, trace metals, and vitamins (-N); or nitrogen, trace metals, and vitamins (-P). Error bars are 95% confidence intervals to medians based on six and 10 replicates for the southeast sector and central sector, respectively.

1992 than 1978–1979 in all sectors of the bay; the increases amounted to 60–90% in the southeast sector of the bay and 40–60% in the central and northwest sectors.

With one exception, inorganic nutrient and particulate concentrations measured during 1989–1992 were lower in the nearshore ocean than at any of the bay stations. The nearshore ocean phosphate concentration, however, was as much as twice the values measured in the bay.

DISCUSSION

In many respects the water column of Kāne'ohe Bay is more oligotrophic now than in the year following sewage diversion. Inorganic nutrient concentrations are down, and inorganic nitrogen and phosphate now border on the limit of detection by traditional colorimetric methods. Chlorophyll *a* concentrations have declined by 35–40% (0.3–0.5 mg m^{-3}), and Secchi depths have increased by 15–35% (1.0–1.5 m) in the southeast sector of the bay. This has happened despite a population increase of 7762 persons (47,335 → 55,097) in the watershed from 1980 to 1990. About 68% of that increase has been in the watershed of the southeast sector (DPEDT 1992). The only evidence of eutrophication has been in the central and northwest sectors of the bay, where there has been about a 15% increase in chl *a*, a 65–70% in-

TABLE 2

COMPARISON OF KĀNE'OHE BAY WATER QUALITY PARAMETERS, 2 JUNE 1978–15 JUNE 1979 VERSUS 4 OCTOBER 1989–10 JUNE 1992

		STATION			
COMPOUND	TIME PERIOD	OF	SE	CE	NW
NO_3 (μM)	1978–1979	0.10	0.03	0.03	0.66
	1989–1992	0.08	0.08	0.07	0.17
NH_4 (μM)	1978–1979	0.47	0.41	0.22	0.27
	1989–1992	0.02	0	0.03	0.05
PO_4 (μM)	1978–1979	0.16	0.15	0.07	0.07
	1989–1992	0.03	0.05	0.03	0.03
Si (μM)	1978–1979	15.5	11.9	9.1	8.1
	1989–1992	7.9	7.1	5.4	3.9
PN (mg m^{-3})	1978–1979	45.4	38.4	20.7	20.0
	1989–1992	44.5	42.5	33.8	36.4
$NO_3 + NH_4$ + PN (μM)	1978–1979	3.81	3.18	1.73	2.36
	1989–1992	3.28	3.12	2.51	2.82
Chl *a* (mg m^{-3})	1978–1979	1.25	0.88	0.43	0.48
	1989–1992	0.76	0.58	0.50	0.54
PC (mg m^{-3})	1978–1979	200	181	114	123
	1989–1992	229	224	180	206
PC/PN (by weight)	1978–1979	4.4	4.7	5.5	6.2
	1989–1992	5.1	5.3	5.3	5.7
PN/chl *a* (by weight)	1978–1979	36.3	43.6	48.1	41.7
	1989–1992	58.6	73.3	67.6	67.4
PC/chl *a* (by weight)	1978–1979	160	206	265	256
	1989–1992	301	386	360	382
Secchi depth (m)	1978–1979	4.5	6.0	8.0	7.5
	1989–1992	6.0	7.0	7.0	7.0

TABLE 3

PERCENTAGE OF CHL *A* ACCOUNTED FOR BY PICOPLANKTON IN KĀNE'OHE BAY AND NEARSHORE OCEAN

STATION				
OF	SE	CE	NW	OCN
39	40	38	41	64

crease in PC and PN, and a 0.5–1.0 m decrease in average Secchi depths.

Rainfall in the Kāne'ohe Bay watershed can vary dramatically from year to year. The impact of land runoff on water quality during a time interval of one or a few years can therefore depend very much on the time interval in question. Figure 4 shows annual average monthly rainfall from 1977 to 1992 recorded by the U.S. Geological Survey (USGS) at its Kāne'ohe Mauka and Waiāhole weather stations (Figure 1). The average rainfall at these two stations was 27 cm per month during the 1978–1979 fieldwork. The corresponding rainfall during the 32 months of the 1989–1992 study was 25 cm/month, a difference of 8%. The USGS similarly maintains gauging stations on Kamo'oali'i Stream, Waihe'e Stream, and Waikāne Stream (Figure 1), three of the major streams entering the bay (Freeman 1993). The average discharges from these three streams during the

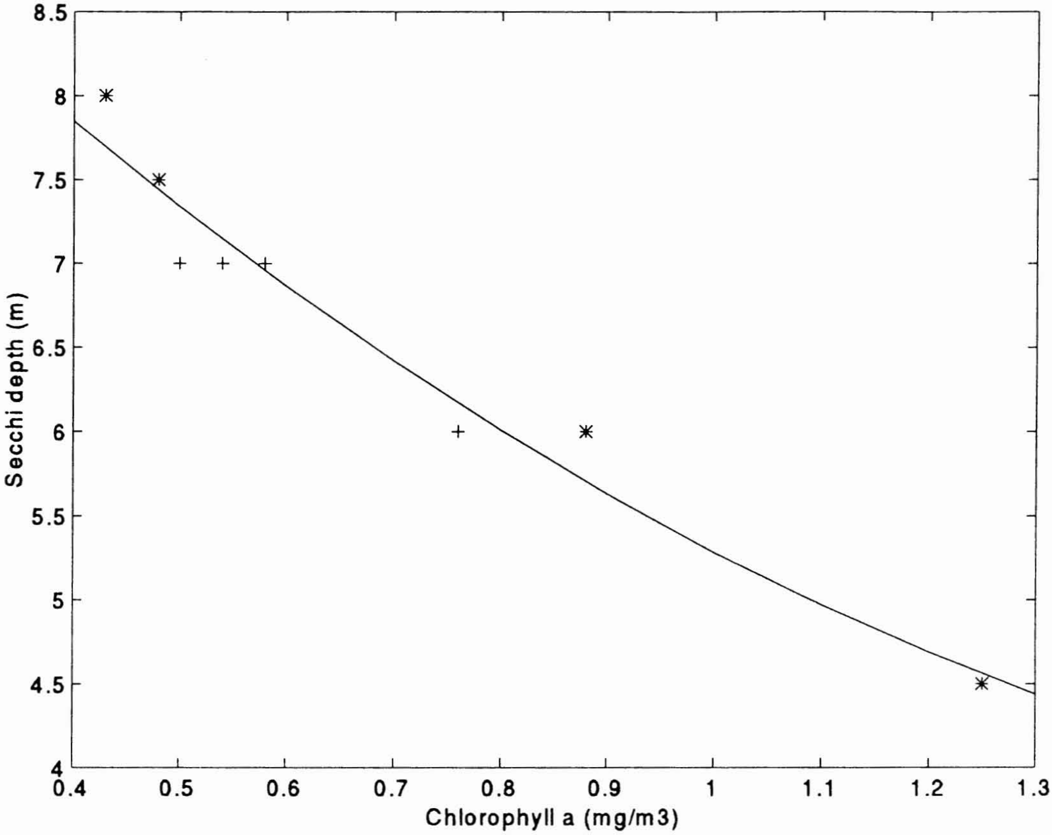

FIGURE 3. Relationship between median chl *a* concentrations and median Secchi depths at the four inner bay water quality stations during 1978–1979 (*) and 1989–1992 (+). The smooth curve drawn through the data is a second-order polynomial fit by least squares and corresponds to the equation $y = 10.2 - 6.5x + 1.6x^2$, where y is the Secchi depth (m) and x is the chl *a* concentrations (mg m^{-3}).

1978–1979 and 1989–1992 fieldwork totaled 0.94 m^3 sec^{-1} and 0.84 m^3 sec^{-1}, respectively, a difference of 11%. Thus there is no reason to believe that the two study periods differed greatly in terms of rainfall or stream discharge. Furthermore, an examination of the relationship between rainfall and stream discharge (Figure 5) shows no significant difference between the periods 1977–1984 and 1985–1992. Hence there is no evidence that the increase of 16% in the size of the human population of the watershed between 1980 and 1990 altered land use patterns in a way that significantly changed the relationship between rainfall and stream discharge.

Some appreciation of the impact of land runoff on water quality in Kāneʻohe Bay can be obtained from the data presented here and in an earlier report by Freeman (1993). Freeman estimated external loadings of nitrogen and phosphorus to the bay based on a lumped-sum parameter model that provided estimates of direct runoff, stream flow, sediment loads, and pollutant loads using existing statistical relationships. There is also some use of the universal soil loss equation to estimate sediment loads from construction sites and agricultural areas. The forcing function in the model is rainfall. A summary of the nitrogen and phosphorus loads is given in Table 4. An important point about the data is that about half the estimated N and P

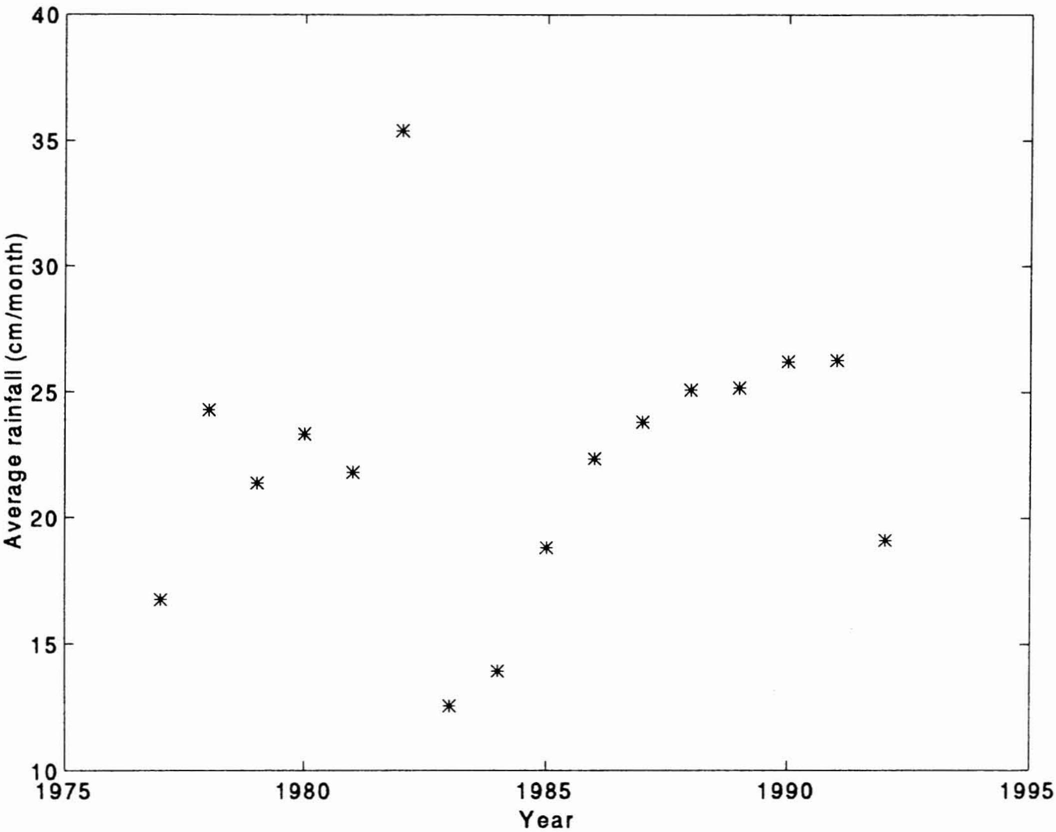

FIGURE 4. Average of annual rainfall recorded at Kāne'ohe Mauka and Waiāhole weather stations from 1977 to 1992.

loads come from cesspool leakage, which is rather insensitive to changes in rainfall and stream runoff.

A source of external nutrients ignored by Freeman is the nutrients in the seawater that flows into the bay over the barrier reef. The amount of seawater that enters the bay over the reef has been estimated by Bathen (1968) to be 1.14×10^{10} m^3 yr^{-1}. To put this in perspective, the nutrient input from seawater would equal the total nutrient loading estimated by Freeman if the total nitrogen and phosphorus concentrations in the seawater equaled 0.65 μM and 66 nM, respectively. Our results (Table 1) indicate that the concentration of phosphate in the nearshore ocean is ca. 60 nM, and although the inorganic nitrogen concentrations border on the limit of detection, the dissolved organic N and P concentrations are ca. 4.5 and 0.3 μM, respectively (Smith et al. 1981). Thus the water that flows over the barrier reef may be a very important source of nutrient loading to Kāne'ohe Bay, particularly to the central and northwest sectors.

Consistent with this analysis is the time series of chl *a* concentrations measured on a weekly basis at the OF station. The chl *a* data reported in Table 1 at the OF station are in fact part of a longer time series that extends from September 1976 to the present, with a gap from July 1979 to May 1982. The

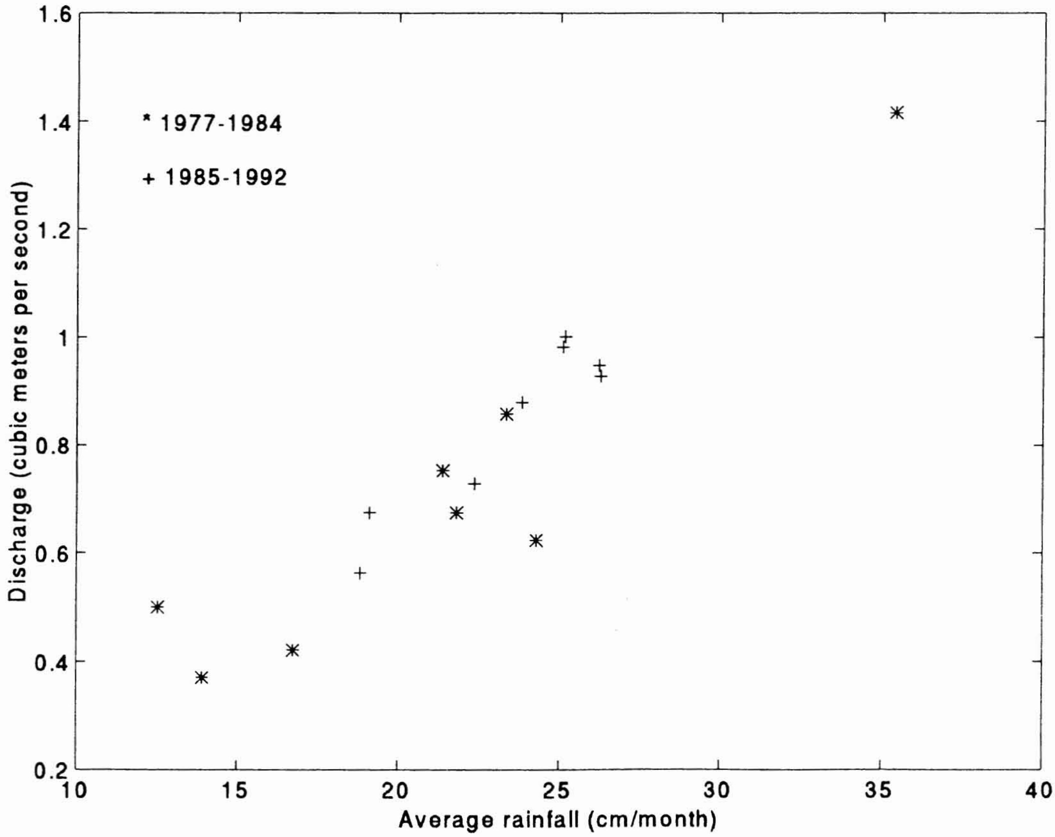

FIGURE 5. Relationship between averge annual rainfall at Kāne'ohe Mauka and Waiāhole weather stations and total annual stream discharge from Kamo'oali'i, Waihe'e, and Waikāne Streams from 1977 to 1992.

TABLE 4

ESTIMATES OF MEAN NITROGEN AND PHOSPHORUS LOADS TO KĀNE'OHE BAY FROM FREEMAN (1993)

LOADS		TONNES yr^{-1}
Nitrogen loads	Total nitrogen	104
	Total nonpoint source N	52
	Nonpoint source urban N	4
	Spring/basal N	2
	Cesspool N	52
Phosphorus loads	Total phosphorus	23.5
	Total nonpoint source P	10.3
	Nonpoint source urban P	4.4
	Spring/basal P	0.7
	Cesspool P	13.2

time series (Figure 6) clearly shows the decline of chl *a* following the sewage diversions in 1977–1978 and the sharp rise and fall of chl *a* following the heavy winter storm in 1987–1988. However, when the annual average discharge from Kamo'oali'i Stream is plotted against the annual average chl *a* concentration at the OF station for the past 9 yr, there is very little correlation at stream discharges below ca. 0.4 m^3 sec^{-1} (Figure 7). The implication of Figure 7 is that there is a background nutrient input that sustains the chl *a* concentration at the OF station at a level of ca. 0.5–1.0 mg m^{-3} and that the stream nutrient inputs do not become sig-

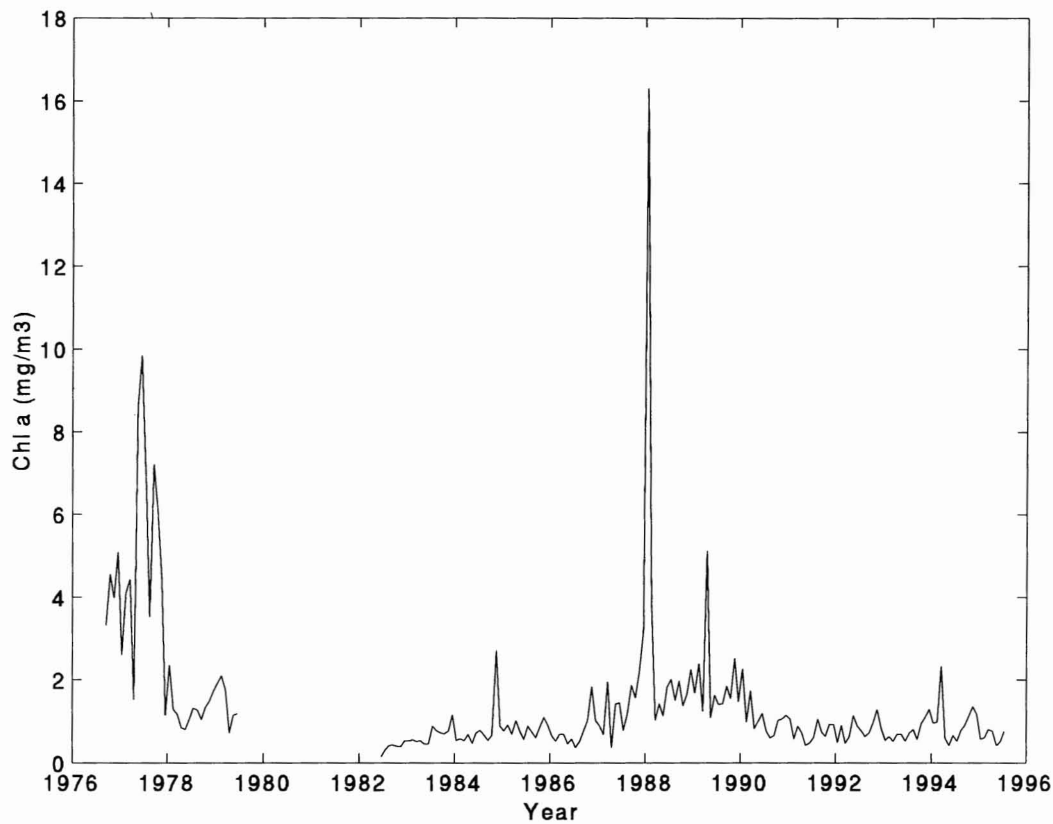

FIGURE 6. Monthly mean surface water chl *a* concentrations measured near site of Kāne'ohe municipal sewer outfall from September 1976 to July 1995.

nificant until the annual average Kamo'oali'i Stream discharge exceeds roughly 0.4 $m^3 sec^{-1}$. This conclusion is consistent with the data in Table 4, which indicate that cesspools account for half the freshwater-associated nutrient inputs to the bay. The average discharge from Kamo'oali'i Stream is ca. 0.32 $m^3 sec^{-1}$. Thus, stream inputs become an important source of nutrient loading only when discharge substantially exceeds its average value.

The implication of this analysis is that the changes in the water quality of Kāne'ohe Bay between 1978–1979 and 1989–1992 are probably not to be attributed to changes in the characteristics of stream runoff. What, then, may be the explanation for the decrease of inorganic nutrient concentrations throughout the bay, the lower chl *a* concentrations and improved water clarity in the southeast sector, and the higher chl *a*, PC, and PN concentrations and reduced water clarity in the central and northwest sectors?

Certainly one of the noteworthy changes in the bay between 1978–1979 and 1989–1992 has been the roughly 75% increase in PC and PN in the central and northwest sectors. Although the human population in the watershed of the central and northwest sectors increased by roughly 19% (ca. 2,500 persons) between 1980 and 1990 (DPEDT 1992), the number of cesspools in the watershed decreased from 1172 to 977 during the same time period (D. Nishimura, Honolulu Department of Public Works, pers. comm.). It is therefore unlikely that the increase in PC

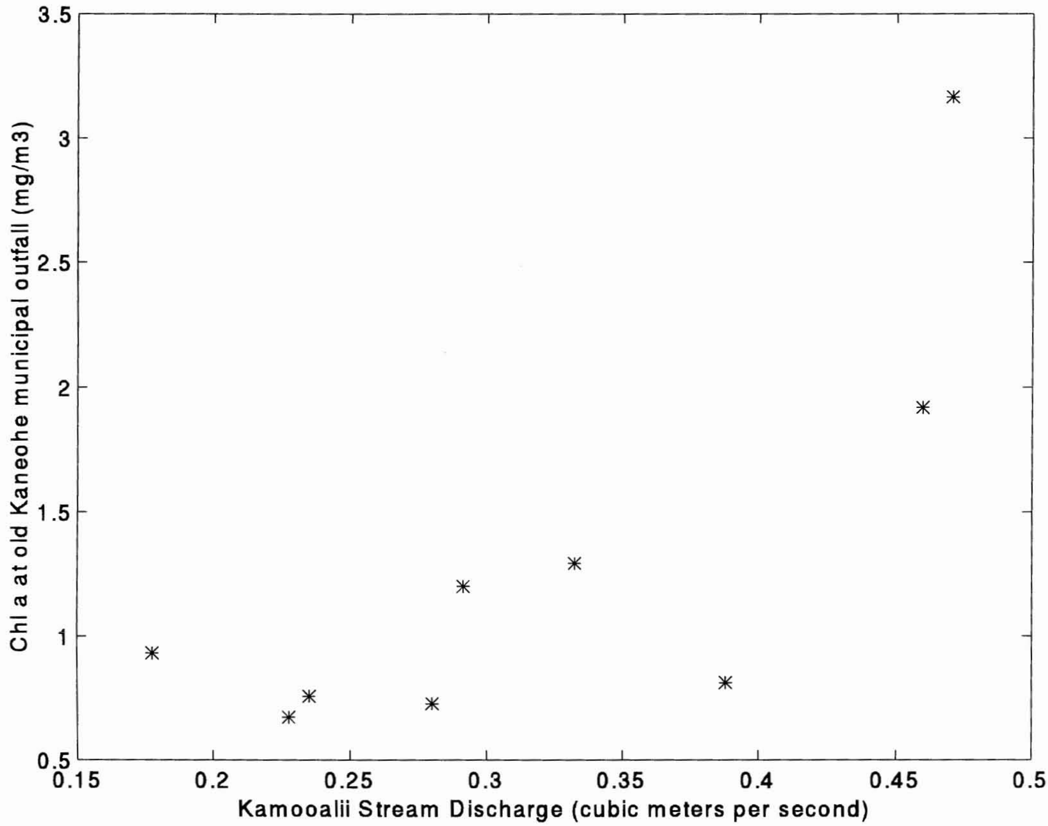

FIGURE 7. Relationship between annual average discharge from Kamo'oali'i Stream and annual average chl *a* concentration at OF site for 9 yr ending in September 1993.

and PN concentrations can be attributed to an increase in nutrient loading from the watershed. A more likely explanation is a change in the metabolic characteristics of the coral reefs, particularly the barrier reef. Reported nitrogen fixation rates on healthy coral reefs are variable, an average figure being ca. 25 g N m^{-2} yr^{-1} (Capone 1983). Multiplying this value by the area of the barrier reef, ca. 5.6 km^2, gives an annual nitrogen fixation rate of ca. 140 tonnes N. This figure exceeds the total N loading estimated by Freeman (Table 4), and even if only half this amount of nitrogen were exported into the lagoon, the impact on water quality would be consequential.

To what extent nitrogen fixation on reefs in the bay may have been suppressed during the period of sewage discharges is unknown, but there is no doubt that both photosynthetic rates and calcification rates were abnormally low on patch and fringing reefs during that time (Kinsey 1979). Maragos (1972) estimated that 24% of the corals in the lagoon portion of the bay had been killed by overgrowth of the alga *Dictyosphaeria cavernosa* (Forsskål) Børgesen during the time of sewage discharges to the bay. Hunter and Evans's (1995) benthic survey work showed that coral coverage in Kāne'ohe Bay had roughly doubled between 1971 and 1990 and that this increase was accompanied by a comparable decrease in the coverage of *D. cavernosa*. If nitrogen fixation rates on the barrier reef were depressed during the period of sewage discharges and if recovery following diversion of the outfalls required more than a few months, then the 75% increase in PN concentrations in the lagoon between 1978–1979 and 1989–1992 may be the result of an increase in the export of fixed nitrogen by the barrier reef. The increase in PC concentrations would logically follow if the additional nitrogen loading stimulated a comparable increase in photosynthetic carbon fixation.

A second important point about the changes in water quality is the fact that both PN/chl *a* and PC/chl *a* ratios increased dramatically in all parts of the bay; the percentage increase ranged from 40 to 90%. Associated with this change was about a threefold decrease in the gradient of PC/PN ratios between the southeast and northwest sectors of the bay and an almost complete disappearance of the corresponding chl *a* gradient. By 1989–1992 the PC/PN ratios in all sectors of the bay differed by less than 6% from a mean of 5.4 by weight, and the chl *a* concentrations at the SE, CE, and NW stations differed by less than 8% from a mean of 0.54 mg m^{-3}.

The explanation for these changes is most likely a shift in the composition of the plankton community. During the time of sewage discharges and during the year following diversion of the outfalls, the southeast sector exported chl *a* to the central sector of the bay. This export had almost completely disappeared by 1989–1992. There is no doubt that the chl *a* export during the time of sewage discharges was a result of the input of nutrients from the sewer outfalls. Smith et al. (1981), for example, indicated that just before their diversion the outfalls in the southeast sector were introducing ca. 174 tonnes of N and 46 tonnes of P per year. In the year following diversion of these outfalls, there was a net efflux of inorganic N and P from the sediments of the southeast sector because of the reduction in the fallout and decomposition of particulate matter from the water column. This net efflux amounted to ca. 56 kg day^{-1} of N and 12 kg day^{-1} of P (Smith et al. 1981). These figures, if extrapolated to 1 yr, would equal ca. 20 tonnes of N and 4.5 tonnes of P. They are therefore equal to ca. 40% of the total nonpoint source N and P loading to the entire bay estimated by Freeman (Table 4). It seems probable that the elevated chl *a* concentrations in the southeast sector in 1978–1979 were largely the result of this sediment nutrient release.

Smith et al. (1981: 372) estimated that "The 30-cm sediment dissolved nutrient reservoir before sewage diversion was enough to account for less than two months' release at the prediversion rate." Thirty centimeters was estimated to be the depth of active biological stirring (bioturbation) in the bay. The 30-cm sediment particulate nutrient reservoir before sewage diversion, although large enough to have maintained prediversion release rates for at least several decades, was characterized by Smith et al. (1981: 372) as "largely refractory." In fact, phosphorus and nitrogen release rates from the sediments declined by 30 and 40%, respectively, during the first year after sewage diversion (Smith et al. 1981). The implication is that a substantial portion of the sediment particulate nutrient reservoir was indeed refractory and contributed little to the release of nutrients from the sediments. Assuming this to be the case, it seems likely that the net efflux of N and P from the sediments of the southeast sector would have declined to an inconsequential level by 1989–1992. This probably explains the lack of a chl *a* gradient between the southeast sector and the rest of Kāne'ohe Bay in 1989–1992.

It seems fair to say that the phytoplankton that were produced in the southeast sector during the time of sewage discharges and in 1978–1979 were growing in a high nutrient environment. Although nutrient enrichment studies have always indicated nitrogen to be more limiting than phosphorus in the bay (Laws and Redalje 1979, 1982), Caperon et al. (1971), in discussing the nutrient regime in the bay, noted (p. 604), "None of the fixed nitrogen values is in the nutrient-limiting range for phytoplankton adapted to oligotrophic environments." The inorganic nitrogen concentrations measured during 1989–1992 are, however, at levels that are limiting, even to phytoplankton adapted to oligotrophic environments.

Several studies have shown that phytoplankton communities in eutrophic environments tend to contain a higher percentage of large cells than do communities in oligotrophic environments (Malone 1971*a*, *b*, Suttle et al. 1987). Furthermore, large cells tend to have higher half-saturation constants for growth and uptake of limiting nutrients than small cells (Eppley et al. 1969). The production and export of phytoplankton from the relatively eutrophic waters of the southeast sector to the rest of Kāne'ohe Bay may therefore explain why the inorganic nitrogen and phosphate concentrations in the bay were not drawn down to levels associated with nutrient limitation in oligotrophic environments during 1978–1979 and during the period of sewage discharges. The last forcing function maintaining eutrophic conditions in the southeast sector would have been the net efflux of nutrients from the sediments. Assuming that efflux had declined to an inconsequential level within a few years of the diversion of the sewer outfalls, it is reasonable to assume that the phytoplankton community in the bay would have evolved toward a community dominated by small cells with the ability to draw down inorganic nitrogen and phosphate concentrations to nanomolar levels. This probably explains why the inorganic nitrogen and phosphate concentrations are so much lower now than in 1978–1979.

The drawdown of silicate concentrations may be accounted for by similar reasoning, assuming that diatoms are an important part of the current phytoplankton community. It is well known that diatoms were abundant in Kāne'ohe Bay during the time of sewage discharges (Murphy 1972). Taguchi et al. (1993) conducted pigment analyses at the OF station on 17 occasions during 1990. The median chl *a* concentration they measured was 0.79 mg m^{-3}, virtually identical to the median value for our larger data set (Table 1). A summary of some of their pigment analyses is given in Table 5. It is obvious from Table 5 that the Kāne'ohe Bay phytoplankton community contains significant numbers of algae from classes other than the Bacillariophyceae, because only fucoxanthin of the auxiliary pigments in Table 5 is associated with diatoms. Given the chl *a*/fucoxanthin ratio of 4.16 used by Laws et al. (1994) for diatoms, we estimate that diatoms accounted for ca. 45% of the chl *a* at the OF station during 1990. Thus, diatoms continue to be an important component of the phytoplankton community in Kāne'ohe Bay. The reduction of silicate concentrations in all parts of the bay between 1978–1979 and 1989–1992 therefore seems reasonable if the diatom community has shifted toward small species with lower half-saturation constants for growth and uptake of silicate.

In their study, Smith et al. (1981) reported concentrations of "net" chl *a*, defined as the chl *a* retained on 35-μm netting. Their results show that the percentage of net chl *a* declined in all parts of the bay in the year following sewage diversion. In 1978–1979, net chl *a* accounted for 5.2–6.0% of the chl *a* in Kāne'ohe Bay. Unfortunately, no previous

TABLE 5

MEDIAN CONCENTRATIONS OF CHL *a* AND DIAGNOSTIC PHOTOSYNTHETIC PIGMENTS IN KĀNE'OHE BAY MEASURED ON 17 OCCASIONS DURING 1990

PIGMENT	ASSOCIATED ALGAL CLASS	CONCENTRATION (μg m^{-3})
Chlorophyll *a*	All algae	790
Chlorophyll *b*	Chlorophytes	22
19'-Butanoyloxyfucoxanthin	Chrysophytes	14
Fucoxanthin	Bacillariophytes	86
19'-Hexanoyloxyfucoxanthin	Prymnesiophytes	43
Peridinin	Dinoflagellates	18
Prasinoxanthin	Prasinophytes	0
Zeaxanthin	Cyanobacteria	99

studies have reported the abundance of picoplankton in Kāne'ohe Bay, and it is therefore impossible to say whether the fact that 40 $\pm$ 1% of the chl *a* in the bay is now accounted for by picoplankton represents a large change from conditions in 1978–1979 or earlier times. The genus *Synechococcus*, which is often an important component of the picoplankton, was not even discovered until 1979 (Johnson and Sieburth 1979, Waterbury et al. 1979). Based on the pigment analysis in Table 5 and an assumed chl *a*/zeaxanthin ratio of 2.1 in *Synechococcus* (Letelier et al. 1993), we estimate that *Synechococcus* sp. accounts for somewhat more than 25% of the chl *a* in the bay. It is thus likely that more than half of the picophytoplankton in Kāne'ohe Bay are cyanobacteria of the genus *Synechococcus*.

The increases of 40–90% in the PN/chl *a* and PC/chl *a* ratios between 1978–1979 and 1989–1992 may bear on the cell size question. Phytoplankton grown under low light intensities have a lower PC/chl *a* ratio than phytoplankton grown under high light intensities (Falkowski 1980). The amount of light that impinges on a phytoplankton cell is proportional to the area of the cell. The work of Montagnes et al. (1994) indicated that the carbon content of marine phytoplankton is proportional to cell volume raised to the 0.99 power. Assuming that cell area scales as cell volume raised to the 2/3 power, the amount of light impinging on a phytoplankton cell per unit cell carbon should vary as cell volume raised to the $0.67 - 0.99 = -0.32$ power. Thus, to achieve a given growth rate large cells require more light-harvesting pigments than small cells and hence have a smaller PC/chl *a* ratio. Cuhel and Waterbury (1984), for example, found that a strain of *Synechococcus* grown in batch culture at a rate of 1.25 day^{-1} had a PC/chl *a* ratio of 133. For comparison, Laws and Bannister (1980) found a PC/chl *a* ratio of 41 in a nutrient-saturated culture of the diatom *Thalassiosira weissflogii* grown at a similar rate of 1.15 day^{-1}. The carbon cell quotas of *Synechococcus* sp. and *T. weissflogii* are ca. 0.3 and 60 pg $cell^{-1}$, respectively (Cuhel and Waterbury 1984, Montagnes et al. 1994). Thus, assuming that phytoplankton growth rates in the bay did not change greatly between 1978–1979 and 1989–1992, the increases in PN/chl *a* and PC/chl *a* are consistent with a shift in the size spectrum of the phytoplankton community toward smaller cells.

An alternative explanation for the increase in PC/chl *a* ratios would be a decrease in phytoplankton growth rates, because phytoplankton PC/chl *a* ratios are negatively correlated with nutrient-limited growth rates (Laws and Bannister 1980). Phytoplankton PN/chl *a* ratios, however, are relatively insensitive to changes in nutrient-limited growth rates, and hence the 40–70% increase in PN/chl *a* ratios between 1978–1979 and 1989–1992 cannot be explained on the basis of a reduction in nutrient-limited growth rates. There is probably, however, an element of truth to the nutrient limitation argument. The largest increases in PC/chl *a* ratios (almost 90%) occurred at the OF and SE stations, and at the same stations the PC/PN ratios increased by 11–16%. Because PC/PN ratios are negatively correlated with nutrient-limited growth rates (Goldman 1980), it seems reasonable to conclude that phytoplankton growth rates have declined somewhat in the southeast sector of the bay since 1978–1979. The constancy of the PC/PN ratios throughout the bay in 1989–1992 suggests that phytoplankton are now growing at comparable rates in all parts of the bay.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of David Hashimoto with the chemical analyses and Lloyd Watarai with the field sampling. This paper benefitted greatly from the critical reviews of Paul Bienfang and one anonymous reviewer.

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